Letter Report

MILDOS-AREA: An Update with Incorporation of *In Situ* Leach Uranium Recovery Technology[*]

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1 INTRODUCTION

The MILDOS-AREA computer code was developed at Argonne National Laboratory in 1989 (Yuan et al. 1989) for evaluating radiological impacts of uranium processing facilities. The code was modified from the original MILDOS code (Strenge and Bander 1984) to include large-area sources and to incorporate changes in methods for dosimetry calculations. MILDOS-AREA estimates the radiological impacts of airborne emissions of radioisotopes of the uranium-238 series. Two different measures are calculated: dose commitments to human receptors and annual average air concentrations.

MILDOS-AREA incorporated dose conversion factors derived by the International Commission on Radiological Protection (ICRP) recommendations of 1978. The annual average air concentrations were compared with the maximum permissible concentrations (MPCs) in the U.S. Nuclear Regulatory Commission's *Standards for Protection against Radiation* (10 CFR Part 20). On January 1, 1994, a revision to 10 CFR Part 20 (revised Part 20) went into effect. The revised Part 20 updated its dosimetry to the ICRP 1978 recommendations. The dose limit to the general public also changed. The changes led to a revision of the calculated allowable concentrations for unrestricted areas, with MPC being replaced by the term "effluent concentrations." Therefore, the calculations performed by MILDOSAREA were not consistent with the current terminology and data contained in the revised Part 20.

In addition, a new method of recovering uranium gained popularity in the late 1980s, and now the majority of operating licensees use the *in situ* leach (ISL) method. In a typical ISL mining site (Hunter 1996), a licensee uses a series of injection wells that introduce dissolved oxygen and sodium carbonate/bicarbonate into the ore zone. The uranium is mobilized and is extracted through a series of pumping wells. The uranium-rich water is routed through a processing building, where the uranium is removed from the water by ion-exchange (IX) columns. The loaded IX resin is then processed to remove the uranium (elution). The eluted uranium is further processed into a concentrated uranium slurry. The slurry is then dried into yellow cake(U_3O_8). The dried U_3O_8 is packaged and shipped for further processing into enriched uranium and reactor fuel.

Some ISL facilities have smaller processing plants remote from the main processing plant. These plants, called satellite facilities, generally will collect the uranium in resin tanks and then ship the loaded resin to the main processing plant for elution, drying, and packaging. The satellite facilities allow the licensee to economically mine uranium a distance away from the main processing plant.

2 PROJECT OBJECTIVES

The overall objective of this project is to update the MILDOS-AREA code data structures and terminology to be consistent with revised 10 CFR Part 20. Another objective is the creation of an example problem for ISL facilities. Finally, the above objectives result in the creation of a patch program that will update current versions of MILDOS-AREA to the new version.

This report consists of three components: (1) modification of the data structure of the MILDOS-AREA code, (2) source term derivation for the ISL mining technology, and (3) application of this methodology in the sample problem. Finally, a computer patch program containing this updated information is described. This patch program is to be attached to MILDOS-AREA as an update for the particular application.

3 MODIFICATIONS TO THE MILDOS-AREA CODE

Two sets of modifications are made to the MILDOS-AREA code. These changes reflect both the semantic and the dosimetric revisions implemented in the revised 10 CFR Part 20.

The first modification consists of replacing all occurrences of MPC with allowable concentration (ALC). These changes affect the last page(s) of output for each time step (see Attachment II), where the concentrations of radionuclides in air at each receptor location are reported. These pages are now referred to as the "Results of the ALC Check at this Location."

The second modification consists of replacing the old MPC values in the MILDOS-AREA database with the numbers currently tabulated under Effluent Concentrations (Air - Column 1) in Table 2 of Appendix B to the revised 10 CFR Part 20. An exception is radon-222 (Rn-222), where the ALC is expressed in units of working level (WL). The value for Rn-222 is derived as specified in the text of Appendix B; to revised Part 20; the occupational derived air concentration of 1/3 WL has been divided by 300. Table 3-1 lists the radionuclides and the ALCs used in MILDOS-AREA.

TABLE 3-1 Allowable Concentrations Used in MILDOS-AREA

Radionuclide	AC (Inhalation Class) (pCi/m^3)	Default Inhalation Class
Uranium-238	3(D), 1(W), 0.06(Y)	Y
Uranium-234	3(D), 1(W), 0.05(Y)	Y
Thorium-230	0.02(W), 0.03(Y)	W
Radium-226	0.9 (W)	W
Radon-222	1/900 (*)	(*)
Lead-210	0.6 (D)	D
Bismuth-210	500 (D), 40 (W)	W
Polonium-210	0.9 (D), 0.9 (W)	W

(*) Radon-222 is gaseous; the AC is reported in WLs.

4 SOURCE TERM ESTIMATION FOR A SAMPLE ISL FACILITY

The sources of radioactive effluent from an operating ISL uranium recovery facility include (1) the drilling operation at new well fields, (2) uranium extraction operations at production well fields, (3) drying and packaging of yellow cake, (4) restoration operations at old well fields, and (5) land application areas. The following sections describe a methodology for source term derivation for ISL sites that may be used instead of the methodology presented in NUREG/CR-4088 (Hartley et al. 1985). *Other methodologies may be more appropriate for a particular operating site.*

4.1 New Well Field

Conventional rotary rigs are commonly employed for all drilling activities at an ISL facility. Because all exploration drill holes are drilled by using and are sealed with high-viscosity bentonitic mud to maintain aquifer isolation, no particulates are expected to be released during drilling operations. The only source of radioactive release is the Rn-222 from radium-containing ore cuttings temporarily stored in the mud pit. During the period when the ore cuttings are awaiting disposal while stored in a mud pit, radioactive decay of radium-226 (Ra-226) is producing radon continuously. The amount of Rn-222 available for release, or the maximum release rate, in a year as a result of Ra-226 decay from ore cuttings in storage is assumed to be given by the following expression:

$$Rn_{nw} = 10^{-12} \, E \, L \, [Ra] \, T \, M \, N \, , \tag{1}$$

where

Rn_{nw} = Rn-222 release rate from new well field (Ci/yr),

10^{-12} = unit conversion factor (Ci/pCi),

$[Ra]$ = concentration of Ra-226 in ore (pCi/g),

E = emanating power (dimensionless),

L = decay constant of Rn-222 (0.181/d),

T = storage time in mud pit (d),

M = average mass of ore material in the pit (g), and

N = number of mud pits generated per year.

4.2 Production Well Field

No particulate materials are expected to be released from the production well field because its process streams, from production and injection wells to IX columns in the satellite facility, are all in a closed-loop circuit. The primary radioactive emission from the process streams of the production well field is

Rn-222 gas. In the natural environment, radon emanates continuously in the ground and migrates through the rock or soil by both diffusion and convection. The movement of radon in groundwater in most cases is governed by water transport, rather than by diffusion (Hess et al. 1985; Mueller Associates, Inc. 1986). In an ISL production well field, the radon released from the ore body is readily removed by the process water ("lixiviant") moving through the well field by injection and production wells. The 3.8-day half-life of Rn-222 allows it to circulate along with the process water in the well field over a long time before it decays.

The general equation describing the change in Rn-222 concentration over time in the process water of a well field can be expressed as:

$$V \, \frac{dC_{Rn}}{dT} \; = \; f \, S \; - \; (L \, + \, v) \, V \, C_{Rn} \; - \; (F_p \; + \; F_i) \, C_{Rn} \; , \tag{2}$$

where

V = volume of water in circulation (L),

C_{Rn} = Rn-222 concentration in process water (pCi/L),

f = fraction of radon source carried by circulating water (dimensionless),

S = radon source (pCi/d),

L = decay constant of Rn-222 (0.181/d),

v = rate of radon venting from piping and valves during circulation (1/d),

F_p = "purge" rate of treated water (L/d), and

F_i = water discharge rate from resin unloading of IX columns (L/d).

The balance of the fraction of radon source carried by circulating water accounts for any radon in the mined area that is not swept into the injection-production well loop and remains trapped in the ore zone. The "purge" or "bleed" in the production well field is necessary to maintain a hydraulic cone of depression around each well field to prevent leakage of mining solutions outside the production zone.

The radon source term, S, can be expressed as

$$S = 10^6 \times L\,E\,[Ra]\,A\,D\,P \;,$$ (3)

where

10^6 = unit conversion factor ($\mathrm{cm^3/m^3}$),

E = emanating power of active ore zone (dimensionless),

[Ra] = Ra-226 concentration in ore zone (pCi/g),

A = active area of ore zone ($\mathrm{m^2}$),

D = average thickness of ore zone (m), and

P = bulk density of ore material ($\mathrm{g/cm^3}$).

The water discharge rate from resin unloading, F_i, can be calculated by

$$F_i = N_i\,V_i\,P_i \;,$$ (4)

where

V_i = volume content of IX column (L),

N_i = number of IX column unloadings per day, and

P_i = porosity of resin material.

Under steady-state conditions, the Rn-222 concentration in the process water, C_{Rn}, can be written as

$$C_{Rn} = \frac{10^6\,[Ra]\,A\,D\,P\,E\,L\,f}{(L+v)\,V + F_p + F_i} \;.$$ (5)

When pressure is reduced during purging or when water is aerated during irrigation, radon is readily released to the atmosphere. The amount of Rn-222 available for release from the "purge" is dependent on the water volume purge rate, F_p, and on the Rn-222 concentration in the purged liquid, C_{Rn}. By conservatively assuming that all available radon in the purge water is released, the annual Rn-222 emission is

$$Rn_w = 3.65 \times 10^{-10}\,C_{Rn}\,F_p \;,$$ (6)

where

3.65×10^{-10} = unit conversion factor (Ci/pCi)(d/yr), and

Rn_w = Rn-222 release rate from purge water (Ci/yr).

The annual Rn-222 releases from occasional venting from wellheads and leaking transport piping are

$$Rn_v = 3.65 \times 10^{-10} \ v \ C_{Rn} \ V \ , \tag{7}$$

where Rn_v is the annual Rn-222 release from venting (Ci/yr).

The annual radon-222 discharge from the unloading of the IX column contents is

$$Rn_x = 3.65 \times 10^{-10} C_{Rn} F_i \ , \tag{8}$$

where Rn_x annual Rn-222 release from unloading of IX column content (Ci/yr).

The total annual Rn-222 release from the production well field is the sum of Rn_w, Rn_v, and Rn_x.

The occurrence of radon in water is controlled by the chemical concentration of radium in the host soil or rock and the emissivity of radon into water. Radon enters air-filled pores in the soil mainly because of the recoil of radon atoms on the decay of Ra-226. The fraction of radon formed in the soil which enters the pores is called the emanating power; reported values range from about 1% to 80%, with an average of 20%, depending on soil type, pore space, and water content (Mueller Associates, Inc. 1986). Varying environmental conditions have been found to affect the rate of radon emanation. In particular, moisture has been found to have significant effects on the radon emanation rate. For purposes of conservatively estimating the radon release from ISL well fields, the emanating power is assumed to be 0.25.

4.3 Drying and Packaging of Yellow Cake

For facilities using rotary vacuum dryers for processing yellow cake, no particulate emissions are expected under normal operating conditions. For facilities using thermal drying, stack releases may be

estimated on the basis of information provided by a number of operating ISL uranium recovery facilities. Although more data are needed, the stack release of yellow cake has been estimated to be about 0.05% of the amount produced; however, because the day-to-day variations of particulate release rates can vary by several times, the assumption is that 0.1% of the uranium produced escapes as particulates into the atmosphere, as suggested in the *Final Generic Environmental Impact Statement on Uranium Milling* (NRC 1980).

The particulate release of nuclides other than uranium isotopes is estimated by grab samples reported by ISL facilities (e.g., Semiannual Reports for Highland Uranium Project, Irigary and Christensen Ranch Projects, Crownpoint, and others). On the basis of the field measurements, the conservative assumption is that the activities of thorium (0.15-0.4% of measured values), radium (0.2-0.3%), lead, polonium, and its decay progeny are 0.5% of the U-238 activity in the yellow cake. Furthermore, it may be assumed that the fraction of this activity that is released is the same as the fraction of uranium (0.1%) that is released.

4.4 Restoration Well Field

The basic operating processes of the restoration well field are similar to those of the production well field. Groundwater affected by leaching processes in the production well fields is restored to its premining levels (1) by the "pump and treat" (groundwater sweep) method and by flushing with fresh water injection, and (2) by using the permeative stream from reverse-osmosis treatment units. Like the production well field, no particulate materials are expected to be released from the restoration well field operations. The primary source of radioactive release is the Rn-222 gas in the process water circulating within and discharged from the restoration operations. The annual Rn-222 releases from the restoration well field therefore can be calculated by Equations 6 and 7.

4.5 Releases from Land Application Areas

Radionuclide-containing water, either from purge water from production well fields or from restoration wastewater from restoration well fields, is treated to unrestricted release levels and disposed of by irrigation. Release onto the soil surface will contaminate the soil at the land application areas. The radionuclides adsorbed by the soil will become a source term for radioactive release through wind erosion processes. To estimate this wind-generated source term by using MILDOS-AREA, the radionuclide concentrations in the soil needs to be estimated first. The radionuclide concentration in the contaminated surface soil region of the land application area, C_s, is calculated by

$$C_s = \frac{10^{-3} \; C_{tw} \; V_o \; R_s}{A_s \; S_d \; P_s} \; ,$$
(9)

where

C_s	$=$	radionuclide concentration in the surface soil (pCi/g),
10^{-3}	$=$	unit conversion factor (L/cm^3),
V_o	$=$	total volume of water released onto the land application area (m^3),
C_{tw}	$=$	radionuclide concentration in treated water (pCi/L),
A_s	$=$	area of land application (m^2),
S_d	$=$	assumed depth of contaminated area (m),
P_s	$=$	bulk density of surface soil (g/cm^3), and
R_s	$=$	fraction of radionuclide in irrigation water retained in the soil particles (dimensionless).

The fraction of radionuclides in irrigation water retained in the soil particles, R_s, can be calculated with the following formula:

$$R_s = (1 - \frac{1}{R_d}) \; .$$
(10)

The retardation factor, R_d, can be calculated with the following formula:

$$R_d = 1 + \frac{P_s \; K_d}{w} \; ,$$
(11)

where

K_d =   radionuclide distribution coefficient (cm^3/g), and

w =   soil volume water content (dimensionless).

The volumetric water content of the soil, w, is the fraction of the total porosity of the soil material occupied by water. The radionuclide distribution coefficient is the ratio of the radionuclide equilibrium concentration of the adsorbed radionuclide in soil to the desorbed radionuclide in water. Representative distribution coefficients can be found in the report by Yu et al. (1993).

5.0 EXAMPLE OF SOURCE TERM CALCULATION FOR SAMPLE ISL FACILITY

The following example illustrates some typical calculations that may be used to derive the source term at a hypothetical operating ISL uranium recovery facility. The example covers the potential operations that may result in radionuclide releases to the air from a typical facility. An input file for use by the MILDOS-AREA code is provided for this example (Attachment I), as well as the doses to hypothetical receptors calculated by the code (Attachment II). Note that reasonable assumptions for input parameters have been used for this hypothetical site, *but these input data are not intended to serve as substitutes for data collected at actual operating facilities*.

The layout of the hypothetical site is shown in Figure 5-1. It consists of a main processing facility, a satellite facility, one well field under development (active well field 1, two production well fields (active well fields 2 and 3), a restoration well field, two radium-settling ponds (P1 and P2), a holding pond, and an irrigation plot. Only small portions of the well fields are assumed to be active over any one-year period of operations. Eight receptor locations are identified. Of these, location 5 is included within a cattle grazing area to estimate the dose from consumption of livestock products that may become contaminated from site releases. Source and receptor locations are reported in kilometers east (x coordinate) and north (y coordinate) of the dryer stack in the main processing facility. Negative values of x and y coordinates indicate west and south directions, respectively. Table 5-1 lists the coordinates

FIGURE 5-1 Map of Sample ISL Site (MPF = main processing facility P1 and P2 = radium setting ponds; and SF = satellite facility)
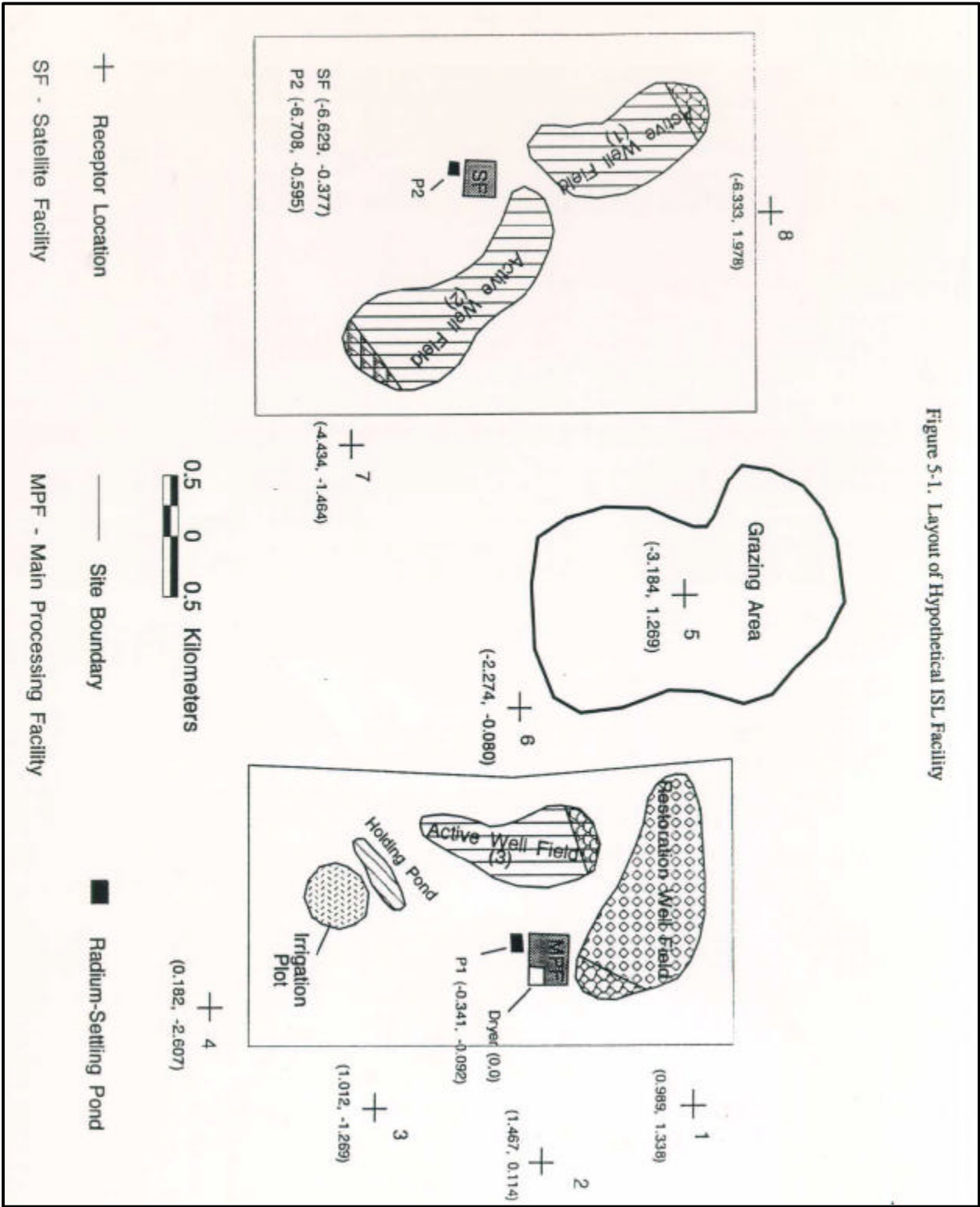

Figure 5-1. Layout of Hypothetical ISL Facility

TABLE 5-1 Source and Receptor Coordinates

Source	East (km)	North (km)	Receptor	East (km)	North (km)
1. Yellow Cake Dryer Stack	0.000	0.000	Receptor 1 (Individual)	0.989	1.338
2. Main Processing Facility IX Columns	0.000	0.000	Receptor 2 (Individual)	1.467	0.114
3. Satellite-Facility	-6.629	-0.377	Receptor 3 (Individual)	1.012	-1.269
4. Radium-Settling Pond 1	-0.341	-0.092	Receptor 4 (Individual)	0.182	-2.607
5. Radium Settling Pond 2	-6.708	-0.595	Receptor 5 (Grazing)	-3.184	1.269
6. Active Well Field 1 (Area Source)	-7.363	1.162	Receptor 6 (Individual)	-2.274	-0.08
	-7.380	1.313	Receptor 7 (Individual)	-4.434	-1.464
	-7.145	1.464	Receptor 8 (Individual)	-6.333	1.978
	-6.893	1.380			
7. Active Well Field 2 (Area Source)	-5.449	-1.489			
	-4.879	-1.053			
	-5.080	-1.438			
	-5.282	-1.556			
8. Active Well Field 3 (Area Source)	-1.423	0.307			
	-1.305	0.525			
	-1.104	0.575			
	-0.886	0.441			
9. Restoration Well Field (Area Source)	-0.248	0.407			
	0.054	0.927			
	0.137	0.575			
	-0.014	0.374			
10. Irrigation Plot (Area Source)	-0.669	-1.839			
	-0.830	-1.825			
	-0.952	-1.704			
	-0.911	-1.448			

used in the input data file for each source and receptor. The meteorology for the site is assumed to be the generic file provided with the code.

5.1 Summary of Principal Operating Characteristics of the Sample ISL Facility

The following parameters apply to the entire facility:

    Yellow cake production rate = 520 metric ton (MT)/yr

    Average ore activity, U-238 and each progeny in secular equilibrium = 280 pCi/g

    Ore porosity = 0.28

    Ore density = 1.8 g/cm^3

5.2 New Well Field Drilling/Construction Area (Well Field 1):

A portion of well field 1, located north of the satellite facility, is under development, as follows:

    Number of new wells per peak year = 600

    Number of new wells per mud pit = 12

    Number of mud pits = 600/12 = 50

    Ore zone thickness = 5 m

    Drill hole diameter = 8 in.

    Average ore material per well (g)= 3.14 $\times$ (8 in / 2 $\times$ 2.54 cm/in)^2 $\times$ 500 cm $\times$

        1.8 g/cm^3 = 2.9 $\times 10^5$

    Total ore material in mud pit per year (g) = 3.5 $\times 10^6$

    Average storage time of ore grade material in mud pits = 12 d

    Radon emanating power = 0.25

For this location, on the basis of an average Ra-226 concentration of 280 pCi/g, the annual Rn-222 emission from the mud pit can be estimated by using Equation 1:

Rn_{nw} = 10^{-12} Ci/pCi $\times$ 0.25 $\times$ 0.181/d $\times$ 280 pCi/g $\times$ 12 d $\times$ 3.5 $\times 10^6$ g $\times$ 50/yr

    = 0.027 Ci/yr

The radon flux can then be estimated by dividing the total emission rate by the area under development as follows:

Area of active drilling per year = 60,000 m^2

Average Rn-222 flux rate = (10^{12} pCi/Ci × 0.027 Ci/yr) / [60,000 m^2 × (3.15 × 10^7 s/yr)]

= 0.0143 pCi/m^2/s

5.3 Production Well Field 2

The following assumptions are used for the production well field located just to the east of the satellite facility:

Operating days per year = 365

Dimensions of the active ore body:

Peak area per year to be mined = 50,000 m^2

Average thickness of ore bodies = 3 m

Total flow volume in circulation in well field = 50,000 × 3 × 0.28 = 42,000 m^3 = 4.2 × 10^7 L

The following assumptions are made for the satellite facility:

Dimensions or capacity of resin column = 3,500 gal

Resin porosity = 0.4

Number of loaded resin unloadings per day = 3

Water discharge rate from unloading of IX column

= 3,500 gal × 0.4 × 3.785 L/gal × 3/d = 1.6 × 10^4 L/d

Total wastewater "purge" rate = 100 gallons per minute (gpm)

= 100 gpm × 3.785 L/gal × 60 min/h × 24 h/d = 5.5 × 10^5 L/d

Fraction of radon source carried by circulating water = 0.8

Rate of radon venting during circulation = 0.01/d

The radon concentration in circulating water is derived by using Equation 5[*] :

C_{Rn} = [(10^6 × 280 × 50,000 × 3 × 1.8 × 0.25 × 0.181) × 0.8] /

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[*]To reduce the lengh of this and other calculations, most of the units have been omitted. The reader is referred back to the equations in Chapter 4 for details on parameter descriptions and units.

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$$\{[0.191 \times (4.2 \times 10^7)] + [(5.5 \times 10^5) + (1.6 \times 10^4)]\}$$
$$= [(3.4 \times 10^{12}) \times 0.8] / (8.6 \times 10^6) = 3.2 \times 10^5 \text{ pCi/L}$$

The radon release rate from purge water into settling pond P2 is derived by using Equation 6:

$$Rn_w = (3.65 \times 10^{-10}) \times (3.2 \times 10^5) \times (5.5 \times 10^5)$$
$$= 64 \text{ Ci/yr}$$

The radon release rate from gas venting and leaking during circulation is derived by using Equation 7:

$$Rn_v = (3.65 \times 10^{-10}) \times 0.01 \times (3.2 \times 10^5) \times (4.2 \times 10^7)$$
$$= 49 \text{ Ci/yr}$$

The radon release rate from IX unloading is derived by using Equation 8:

$$Rn_x = (3.65 \times 10^{-10}) \times (3.2 \times 10^5) \times (1.6 \times 10^4)$$
$$= 1.9 \text{ Ci/yr}$$

The total radon release from production well field 2 = 115 Ci/yr.

5.4 Production Well Field 3

The following assumptions are used for the production well field located just to the west of the main processing facility:

Operating days per year $= 365$

Dimensions of the active ore body:

Peak area per year to be mined $= 55{,}000 \text{ m}^2$

Average thickness of ore bodies $= 5 \text{ m}$

Total flow volume in circulation in well field

$= 55{,}000 \times 5 \times 0.28 = 77{,}000 \text{ m}^3 = 7.7 \times 10^7 \text{ L}$

The same parameters used for the satellite facility servicing well field 2 apply to the IX facility used for well field 3. The following source terms have been derived by using Equations 5 to 8.

The radon concentration in circulating water for well field 3 is given by

$$C_{Rn} = [(10^6 \times 280 \times 55{,}000 \times 5 \times 1.8 \times 0.25 \times 0.181) \times 0.8] /$$
$$\{[0.191 \times (7.7 \times 10^7)] + [(5.5 \times 10^5) + (1.6 \times 10^4)]\}$$
$$= [(6.3 \times 10^{12}) \times 0.8] / (1.53 \times 10^7) = 3.3 \times 10^5 \text{ pCi/L}$$

The radon release rate from purge water into settling pond P1 is given by

$$Rn_w = (3.65 \times 10^{-10}) \times (3.3 \times 10^5) \times (5.5 \times 10^5)$$

$$= 66 \text{ Ci/yr}$$

The radon release rate from gas venting and leaking during circulation is given by

$$Rn_v = (3.65 \times 10^{-10}) \times 0.01 \times (3.3 \times 10^5) \times (7.7 \times 10^7)$$

$$= 93 \text{ Ci/yr}$$

The radon release rate from IX unloading is given by

$$Rn_x = (3.65 \times 10^{-10}) \times (3.3 \times 10^5) \times (1.6 \times 10^4)$$

$$= 1.9 \text{ Ci/yr}$$

The total radon release from production well field 3 = 161 Ci/yr.

5.5 Restoration Well Field

The following assumptions were used for the restoration well field north of the main processing facility:

Expected restoration operation time = 7 yr

Operating days per year = 240

Dimensions of restoration ore body:

Area per year to be restored = 100,000 m^2

Average thickness of ore bodies = 5 m

Total flow volume in circulation in well field

$= 100,000 \times 5 \times 0.28 = 140,000 \text{ m}^3 = 1.4 \times 10^8 \text{ l}$

Total treated water "purge" rate = 200 gpm

$= 200 \text{ gpm} \times 3.785 \text{ L/gal} \times 60 \text{ min/h} \times 24 \text{ h/d} = 1.1 \times 10^6 \text{ L/d}$

Fraction of radon source carried by circulating water = 0.8

Rate of radon venting during circulation = 0.01/d

The following source terms have been derived by using Equations 5 to 7.

The radon concentration in circulating water for the restoration well field is given by

$$C_{Rn} = [(10^6 \times 280 \times 100,000 \times 5 \times 1.8 \times 0.25 \times 0.181) \times 0.8] /$$

$$\{[0.191 \times (1.4 \times 10^8)] + (1.1m \times 10^6)]\}$$
$$= [(1.1 \times 10^{13}) \times 0.8] / (2.8 \times 10^7) = 3.3 \times 10^5 \text{ pCi/L}$$

The radon release rate from purge water into settling pond P1 is given by

$$Rn_w = (240/365) \times (3.65 \times 10^{-10}) \times (3.3 \times 10^5) \times (1.1 \times 10^6)$$
$$= 87 \text{ Ci/yr}$$

The radon release rate from gas venting and leaking during circulation is given by

$$Rn_v = (240/365) \times (3.65 \times 10^{-10}) \times 0.01 \times (3.3 \times 10^5) \times (1.4 \times 10^8)$$
$$= 110 \text{ Ci/yr}$$

The total radon release from the restoration well field = 197 Ci/yr.

5.6 Land Application (Irrigation) Area

The following assumptions are made for the irrigation plot:

Radionuclide concentrations in the holding pond:

U-238 = 1,200 pCi/L

Th-230 = 5 pCi/L

Ra-226 and all progeny = 30 pCi/L

Land irrigation operation water flow rate = 400 gpm

= 400 gpm $\times$ 3.785 L/gal $\times$ 60 min/h $\times$ 24 h/d = 2.2 $\times 10^6$ L/d

Land irrigation operation = 122 d/yr

Land irrigation operation lifetime = 7 yr

Total volume water released over operation lifetime

= (2.2 $\times 10^6$ L/d) $\times$ 122 d/yr $\times$ 7 yr $\times$ 10^{-3} m³/L =1.9$\times 10^6$ m³

Total area of clean wastewater land application = 185,000 m²

Assumed depth of contaminated area = 0.15 m

Density of soil = 1.6 g/cm³

Soil volume water content = 0.25

Distribution coefficient of soil (cm³/g):

Uranium = 50

Thorium = 60,000

Radium = 70

Lead = 100

The retardation factors of surface soil, calculated by using Equation 11, are

Uranium = 320

Thorium = 380,000

Radium = 450

Lead = 640

The fraction of radionuclides in irrigation water that is retained in the surface soil, calculated by using Equation 10, is

Uranium = 1

Thorium = 1

Radium = 1

Lead = 1

The land application area peak surface soil radionuclide concentrations, calculated by using Equation 9, are

U-238 $= (10^{-3} \times 1,200 \times 1.9 \times 10^6 \times 1) / (185,000 \times 0.15 \times 1.6)$

$= 0.043 \times 1,200 = 51$ pCi/g

Th-230 $= 0.043 \times 5 = 0.21$ pCi/g

Ra-226 $= 0.043 \times 30 = 1.3$ pCi/g

Pb-210 $= 0.043 \times 30 = 1.3$ pCi/g

Radon flux $= 1.3$ pCi/g $\times 1.0$ (pCi/m^2/s)/(pCi/g) $= 1.3$ (pCi/m^2/s)

5.7 Main Processing Facility

The following assumptions apply to the main processing facility:

Yellow cake (U_3O_8) production $= 520$ MT/yr

Stack release rate:

U-238

$= 520$ MT/yr $\times 0.001 \times 10^6$ g/MT $\times 0.85$ g U-nat/g $U_3O_8 \times (3.3 \times 10^{-7}$ Ci U-238/g U-nat)

= 0.146 Ci/yr

Th-230

= 0.146 $\times$ 0.005 = 0.00073 Ci/yr

Ra-226, Pb-210, and Po-210

= 0.146 $\times$ 0.005 = 0.00073 Ci/yr

6.0   DESCRIPTION OF PATCH PROGRAM

The revisions to the MILDOS-AREA code are incorporated in the following files:

- **MILMAIN.EXE.** This file is the FORTRAN executable file containing the revisions discussed in Chapter 3. It replaces the old MILMAIN.EXE.

- **SAMPISL.DAT.** This file is the input data file for the example ISL facility described in Chapter 5. It is listed in Attachment I.

- **MILDOS.UPD.** This data file contains the updated allowable concentration levels for the radionuclides listed in Table 3-1.

- **README.TXT**. This text file contains instructions to MILDOS-AREA on how to replace the old MILMAIN.EXE with the new version and how to copy the other two files to the user's MILDOS directory.

7.0 REFERENCES

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